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# Charged Higgs phenomenology beyond the MSSM

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Based on:

H.E.L. and D. MacLennan, Phys. Rev. D79, 115022 (2009)

H.E.L. and D. MacLennan, arXiv:091x.xxxx

S.M. Davidson and H.E.L., arXiv:0906.3335 and work in progress

# Outline

Introduction: the Higgs sector

Charged Higgs in the MSSM and experimental studies

Other models:
- Lepton-specific two Higgs doublet model
- Flipped two Higgs doublet model
- Two-doublet model for neutrino masses

Conclusions

# Introduction: the Standard Model Higgs mechanism on one slide

Introduce a single complex SU(2)-doublet scalar field $\Phi$.
Scalar potential $V = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$ triggers electroweak symmetry breaking:

$$\Phi = \begin{pmatrix} \phi^+ \\ (v + \phi^{0,r} + i\phi^{0,i})/\sqrt{2} \end{pmatrix} \qquad \text{with } v = \sqrt{\frac{\mu^2}{\lambda}}.$$

Physical Higgs is $h^0 = \phi^{0,r}$.
Would-be Goldstone bosons are $G^0 = \phi^{0,i}$, $G^+ = \phi^+$ and can be gauged away ("eaten by the $W$ and $Z$").
Covariant derivative term $(\mathcal{D}^\mu\Phi)^\dagger(D_\mu\Phi)$ gives weak boson masses $M_W^2 = \frac{g^2v^2}{4}$, $M_Z^2 = \frac{(g^2+g'^2)v^2}{4}$.
Yukawas $\mathcal{L} = -y^d_{ij}\bar{d}_{Ri}\Phi Q_{Lj} - y^u_{ij}\bar{u}_{Ri}\tilde{\Phi}Q_{Lj} - y^\ell_{ij}\bar{e}_{Ri}\Phi L_{Lj} + h.c.$ give fermion mass matrices $m^f_{ij} = y^f_{ij}v/\sqrt{2}$; diagonalizing gives fermion masses (with $y^f_{ij}$ diagonalized automatically); CKM matrix from mismatch between $u_L$ and $d_L$ rotations.

## Two automatic features of the Standard Model:

1) Custodial symmetry preserved at tree level:

$$\frac{M_W}{M_Z \cos\theta_W} = 1 \qquad \text{where } \cos\theta_W \equiv \frac{g}{\sqrt{g^2 + g'^2}}.$$

Maintained in extended Higgs sectors if they contain only doublets (and singlets).

Two-doublet models: covariant derivative terms become

$$\mathcal{L} \supset (\mathcal{D}^\mu \Phi_1)^\dagger (D_\mu \Phi_1) + (\mathcal{D}^\mu \Phi_2)^\dagger (D_\mu \Phi_2)$$

Gauge boson masses become

$$M_W^2 = \frac{g^2 v_1^2}{4} + \frac{g^2 v_2^2}{4}, \qquad M_Z^2 = \frac{(g^2 + g'^2) v_1^2}{4} + \frac{(g^2 + g'^2) v_2^2}{4}$$

Preserves $\frac{M_W}{M_Z \cos\theta_W} = 1$; requires $v_1^2 + v_2^2 = v_{SM}^2$.

With two doublets we have four more scalar degrees of freedom:

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ (v_1 + \phi_1^{0,r} + i\phi_1^{0,i})/\sqrt{2} \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ (v_2 + \phi_2^{0,r} + i\phi_2^{0,i})/\sqrt{2} \end{pmatrix}$$

with $v_1^2 + v_2^2 = v_{\rm SM}^2 = 4M_W^2/g^2$ and $v_2/v_1 \equiv \tan\beta$.

Mass eigenstates:

$$\begin{aligned} h^0 &= -\sin\alpha\,\phi_1^{0,r} + \cos\alpha\,\phi_2^{0,r}, & H^0 &= \cos\alpha\,\phi_1^{0,r} + \sin\alpha\,\phi_2^{0,r} \\ A^0 &= -\sin\beta\,\phi_1^{0,i} + \cos\beta\,\phi_2^{0,i}, & G^0 &= \cos\beta\,\phi_1^{0,i} + \sin\beta\,\phi_2^{0,i} \\ H^+ &= -\sin\beta\,\phi_1^+ + \cos\beta\,\phi_2^+, & G^+ &= \cos\beta\,\phi_1^+ + \sin\beta\,\phi_2^+ \end{aligned}$$

Can rotate by angle $\beta$ to "Higgs basis": $s \equiv \sin(\beta-\alpha)$, $c \equiv \cos(\beta-\alpha)$

$$\begin{pmatrix} G^+ \\ (v_{\rm SM} + (sh^0 + cH^0) + iG^0)/\sqrt{2} \end{pmatrix} \qquad \begin{pmatrix} H^+ \\ ((ch^0 - sH^0) + iA^0)/\sqrt{2} \end{pmatrix}$$

Gauge couplings:

$\gamma H^+H^-$, $ZH^+H^-$, $W^-H^+A^0$, $W^-H^+(ch^0 - sH^0)$

## Two automatic features of the Standard Model:

2) No flavor-changing neutral Higgs couplings.

Generic multi-Higgs-doublet model:

$$\mathcal{L}_{\text{Yuk}} \supset -y^d_{ij}\bar{d}_{Ri}\Phi_1 Q_{Lj} - \tilde{y}^d_{ij}\bar{d}_{Ri}\Phi_2 Q_{Lj} + h.c.$$

Mass matrix for down-type quarks: $m^d_{ij} = (y^d_{ij}v_1 + \tilde{y}^d_{ij}v_2)/\sqrt{2}$.
Diagonalizing $m^d_{ij}$ does *not* in general diagonalize $y^d_{ij}$ and $\tilde{y}^d_{ij}$ separately; leads to flavor-changing neutral Higgs couplings.

Flavor-changing neutral Higgs couplings are forbidden if each type of fermion ($u$, $d$, $\ell$) gets its mass from exactly one Higgs doublet: called "natural flavor conservation." [Glashow & Weinberg; Paschos; 1977]

One doublet: $\mathcal{L} = -y^d_{ij}\bar{d}_{Ri}\Phi Q_{Lj} - y^u_{ij}\bar{u}_{Ri}\tilde{\Phi} Q_{Lj} - y^\ell_{ij}\bar{e}_{Ri}\Phi L_{Lj} + h.c.$

Two doublets: four ways to assign fermion couplings ($u$, $d$, $\ell$):

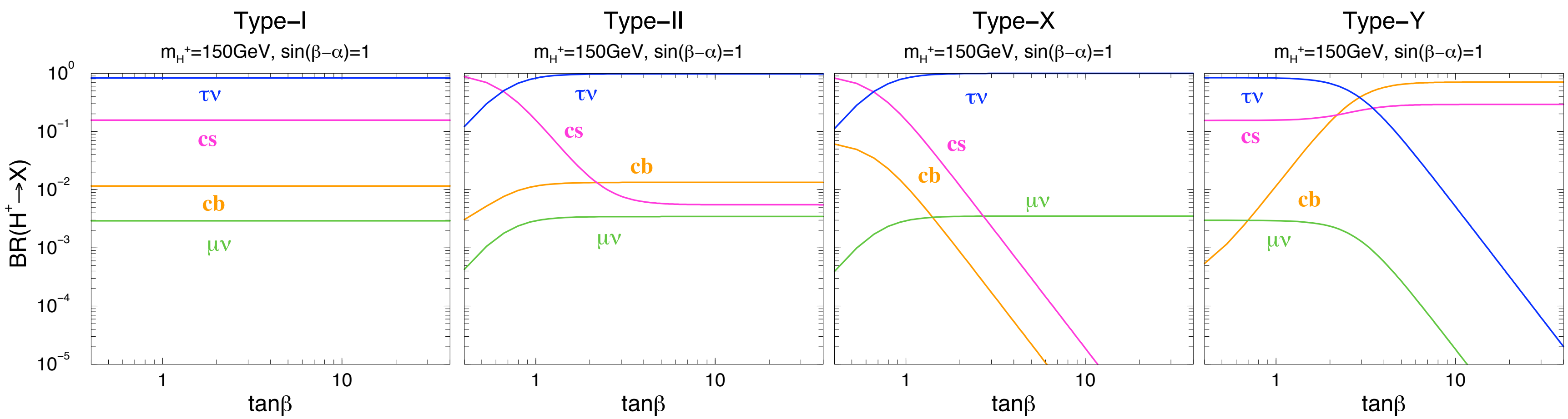
| | Type I | Type II | Leptonic | Flipped |
|---|---|---|---|---|
| $\Phi_1$ | – | $d, \ell$ | $\ell$ | $d$ |
| $\Phi_2$ | $u, d, \ell$ | $u$ | $u, d$ | $u, \ell$ |

Charged Higgs couplings to fermions (all $\times \frac{ig}{\sqrt{2}M_W}$):

| Model | $H^+\bar{u}_i d_j$ | $H^+\bar{\nu}_i\ell_i$ |
|---|---|---|
| Type I | $V_{ij}(\cot\beta\, m_{ui}P_L - \cot\beta\, m_{dj}P_R)$ | $\cot\beta\, m_{\ell i}P_R$ |
| Type II | $V_{ij}(\cot\beta\, m_{ui}P_L + \tan\beta\, m_{dj}P_R)$ | $\tan\beta\, m_{\ell i}P_R$ |
| Leptonic | $V_{ij}(\cot\beta\, m_{ui}P_L - \cot\beta\, m_{dj}P_R)$ | $\tan\beta\, m_{\ell i}P_R$ |
| Flipped | $V_{ij}(\cot\beta\, m_{ui}P_L + \tan\beta\, m_{dj}P_R)$ | $\cot\beta\, m_{\ell i}P_R$ |

Physics controlled by $\tan\beta$ and $M_{H+}$.
Most experimental studies: Type II model (same as in MSSM).

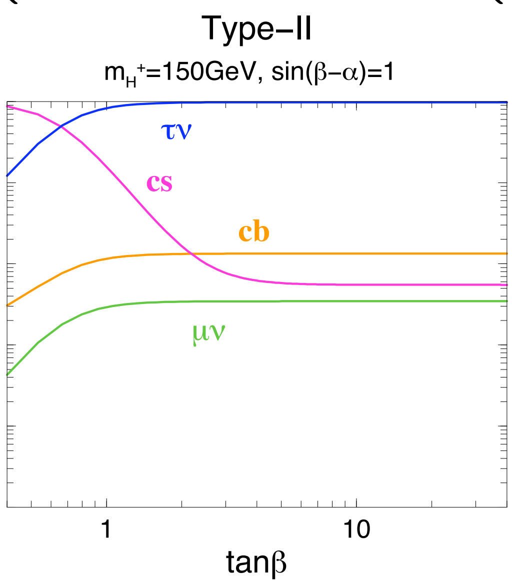
| Model | $H^+\bar{u}_i d_j$ | $H^+\bar{\nu}_i \ell_i$ |
|---|---|---|
| Type I | $V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$ | $\cot\beta\, m_{\ell i} P_R$ |
| Type II | $V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$ | $\tan\beta\, m_{\ell i} P_R$ |
| Leptonic | $V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$ | $\tan\beta\, m_{\ell i} P_R$ |
| Flipped | $V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$ | $\cot\beta\, m_{\ell i} P_R$ |



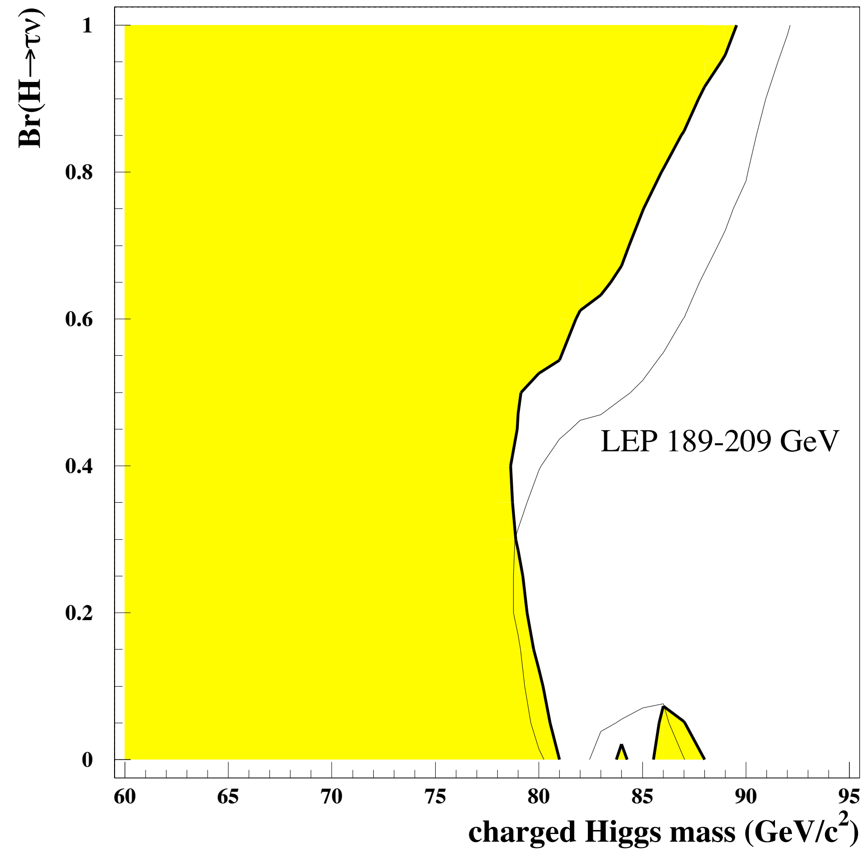

Aoki et al, Phys. Rev. D80, 015017(2009)

# LEP, Tevatron, and LHC

LEP combined limit, assuming
BR($H^+ \to \tau\nu$)+BR($H^+ \to c\bar{s}$) = 1:
$M_{H+} > 78.6$ GeV
(89.6 GeV for BR($H^+ \to \tau\nu$) = 1)




Aoki et al, Phys. Rev. D80, 015017(2009)



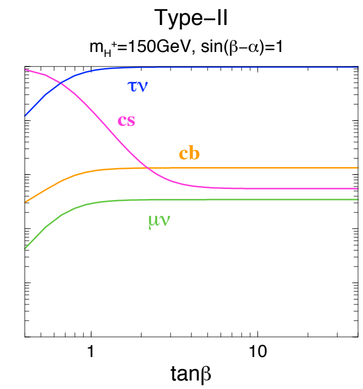

ADLO, hep-ex/0107031

Separate OPAL analysis for BR($H^+ \to \tau\nu$) = 1:
$M_{H+} \geq 92.0$ GeV Abbiendi et al [OPAL], Eur. Phys. J. C32, 453 (2004)

## LEP, Tevatron, and LHC

Tevatron search for charged Higgs in top decay

Type-II model: coupling for $t \to bH^+$ is
$\frac{ig}{\sqrt{2}M_W} V_{tb}(\cot\beta\, m_t P_L + \tan\beta\, m_b P_R)$

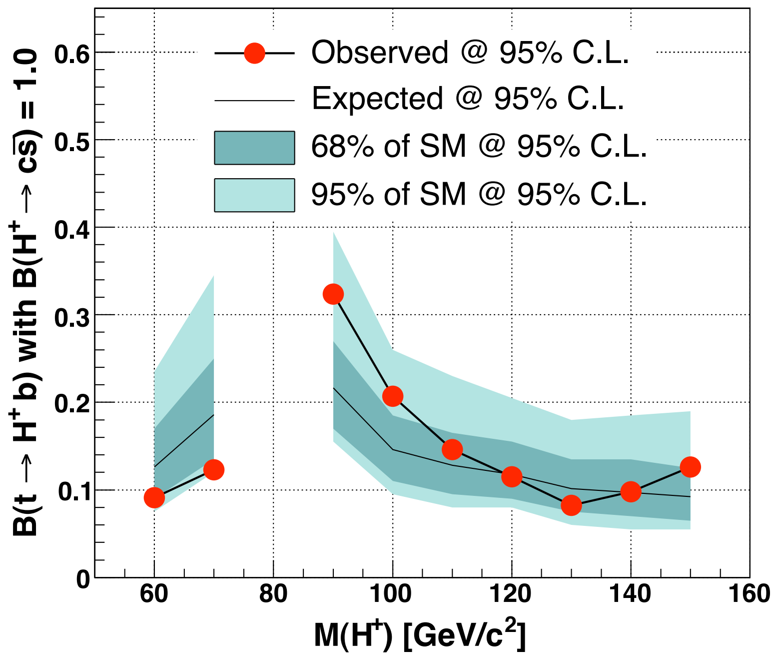


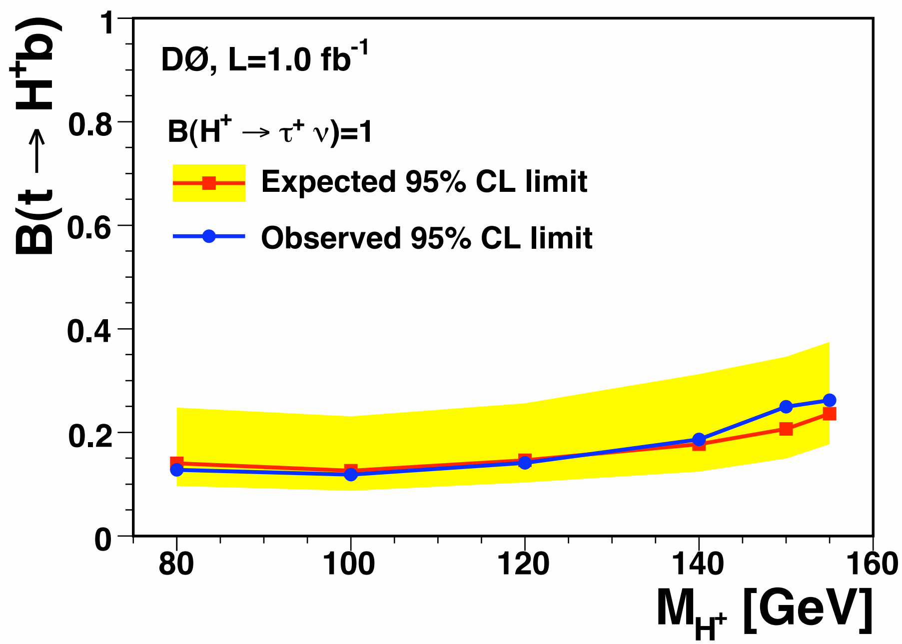

Aoki et al (2009)

BR$(H^+ \to c\bar{s}) = 1$

Look for $M_{jj} \neq M_W$

BR$(H^+ \to \tau\nu) = 1$



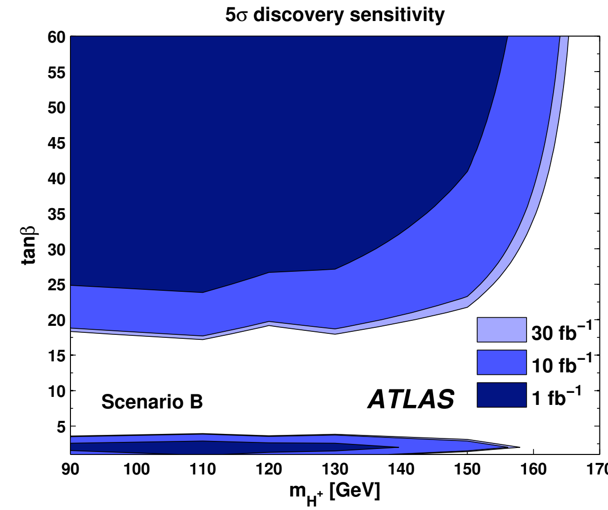




CDF, PRL103, 101803 (2009)

DZero, arXiv:0908.1811

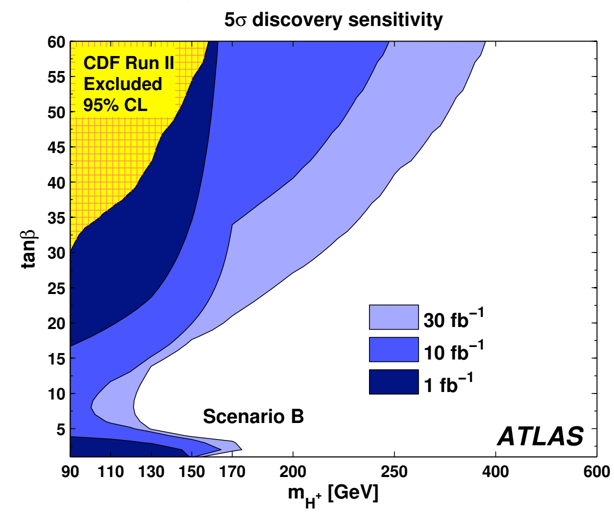
## LEP, Tevatron, and LHC

LHC search prospects: Type II 2HDM




Light charged Higgs:
top decay $t \to H^+ b$ with $H^+ \to \tau\nu$

ATLAS CSC book, arXiv:0901.0512




Heavy charged Higgs:
associated production $tH^+$ with $H^+ \to tb$

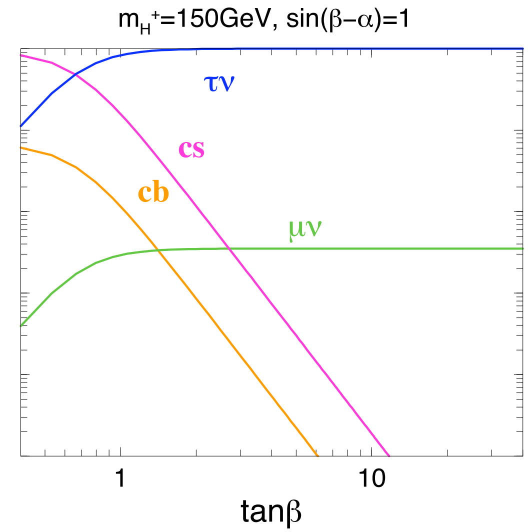
## Lepton-specific two Higgs doublet model

| Model | $H^+\bar{u}_i d_j$ | $H^+\bar{\nu}_i \ell_i$ |
|---|---|---|
| Type II | $V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$ | $\tan\beta\, m_{\ell i} P_R$ |
| Leptonic | $V_{ij}(\cot\beta\, m_{ui} P_L - \cot\beta\, m_{dj} P_R)$ | $\tan\beta\, m_{\ell i} P_R$ |

Couplings to quarks: $\propto \cot\beta$, same pattern as Type I 2HDM.
- Constraint from $b \to s\gamma$ same as in Type-I model: $\tan\beta \gtrsim 4(2)$ for $M_{H^+} = 100(500)$ GeV. [Su & Thomas, PRD79, 095014 (2009)]
- Production rates in $t \to H^+ b$, $tH^+$ associated production suppressed by $\cot^2\beta$.

Couplings to leptons: $\propto \tan\beta$
- Decays to taus usually dominate
- Model used as "messenger" of dark matter for PAMELA/ATIC positron excess [Goh, Hall & Kumar, JHEP 05 (2009) 097]

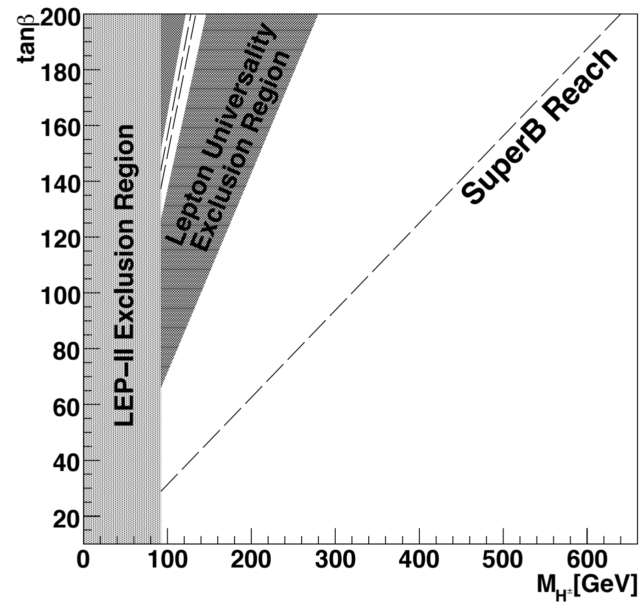
# Lepton-specific two Higgs doublet model: constraints




Below the $tb$ threshold:
decays almost entirely to $\tau\nu$.

[Plot: Aoki et al, PRD80, 015017(2009)]

Use LEP limit from OPAL:
$M_{H+} \geq 92.0$ GeV
Abbiendi et al [OPAL], EPJC32, 453 (2004)



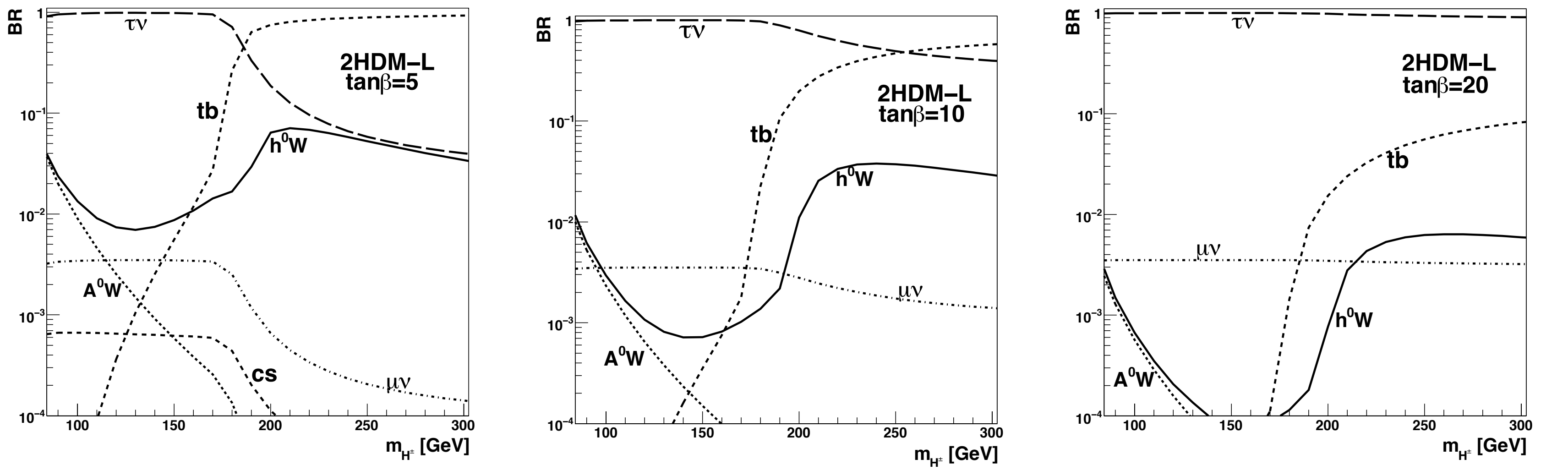

$\tau \to e\nu\bar{\nu}$ vs $\tau \to \mu\nu\bar{\nu}$:
Tree-level charged Higgs exchange affects lepton universality.

[Plot: HEL & D. MacLennan, PRD79, 115022 (2009)]

$M_{H+} \geq 1.4 \tan\beta$ GeV
(plus allowed sliver: 0.61–0.73 $\tan\beta$ GeV)

## Lepton-specific two Higgs doublet model: LHC prospects

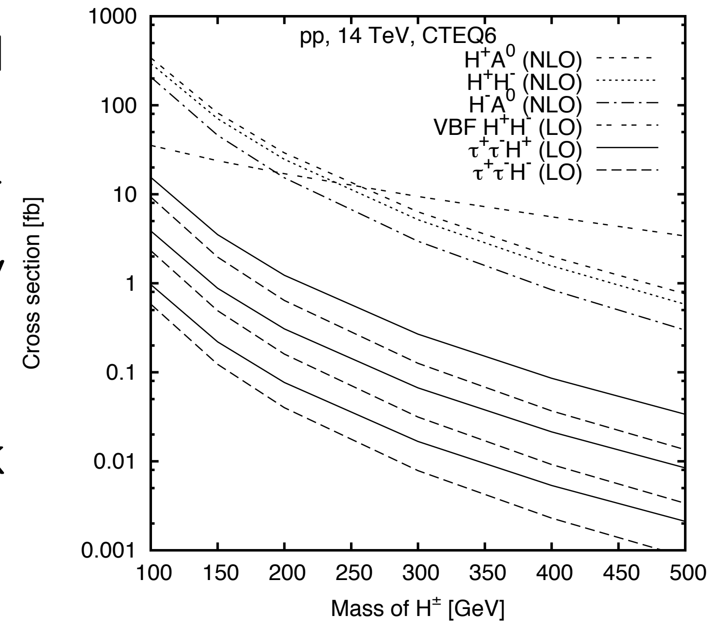
Decays are to $\tau\nu$; also $tb$ above threshold for $\tan\beta$ not too large.




[Plots: HEL & D. MacLennan, PRD79, 115022 (2009)]

Production rates in $t \to H^+ b$, $tH^+$ associated production suppressed by $\cot^2\beta$.

Have to rely instead on electroweak production: $H^+H^- \to \tau^+\tau^- p_T^{\rm miss}$, $H^\pm A^0/H^0 \to \tau^\pm p_T^{\rm miss} \tau\tau$ $(\mu\mu)$

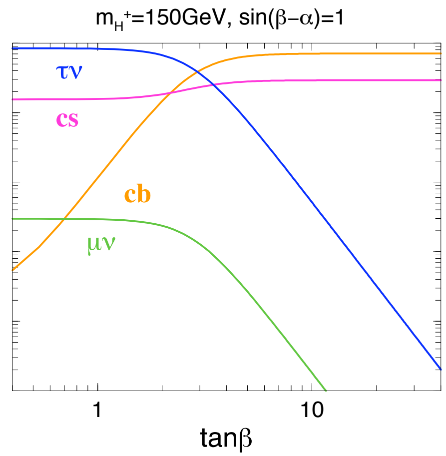


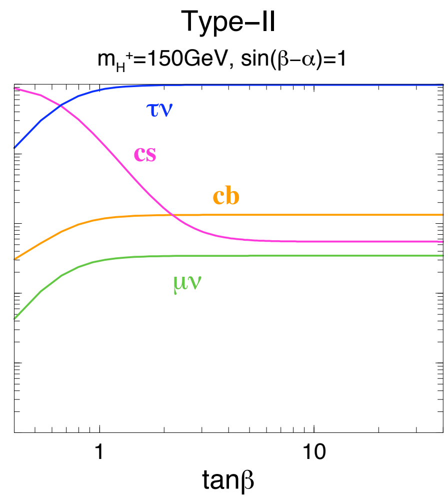
# Flipped two Higgs doublet model

| Model | $H^+\bar{u}_i d_j$ | $H^+\bar{\nu}_i\ell_i$ |
|---|---|---|
| Type II | $V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$ | $\tan\beta\, m_{\ell i} P_R$ |
| Flipped | $V_{ij}(\cot\beta\, m_{ui} P_L + \tan\beta\, m_{dj} P_R)$ | $\cot\beta\, m_{\ell i} P_R$ |

Couplings to quarks: same pattern as Type II 2HDM.
- Constraint from $b \to s\gamma$ same as in Type-II model, $M_{H+} \gtrsim$ 200–300 GeV [modulo cancellations with other flavor-violating contributions]
- Production rates in $t \to H^+ b$, $tH^+$ associated production same as in Type-II.

Couplings to leptons: proportional to $\cot\beta$ instead of $\tan\beta$.




For $\tan\beta \gtrsim 3$:
$H^+ \to c\bar{b}$ about 2/3,
$H^+ \to c\bar{s}$ about 1/3

$H^+ \to \tau\nu$ ~0.9 for $\tan\beta \lesssim 3$.

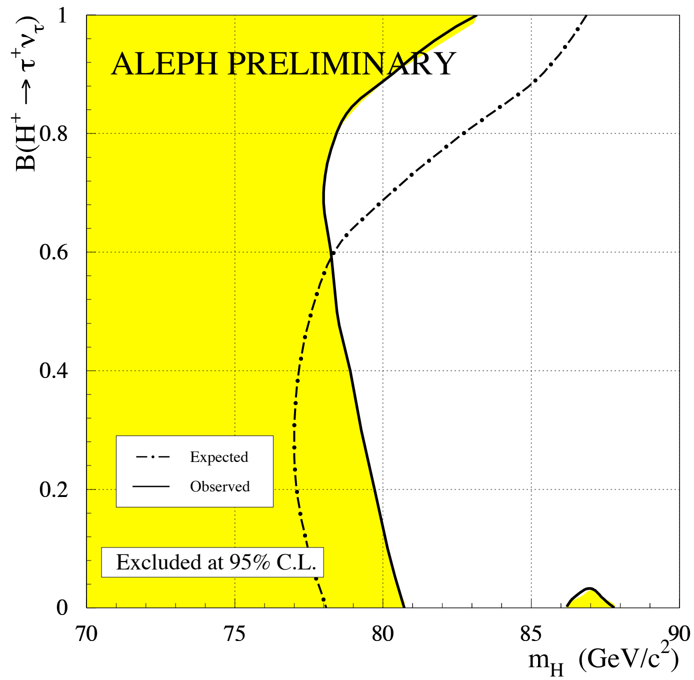
[Plots: Aoki et al, PRD80, 015017(2009)]

## Flipped two Higgs doublet model: constraints

Limits from LEP: Can't use LEP combined: DELPHI and L3 actively rejected $b$s: no good for $H^+ \to c\bar{b}$.
OPAL and ALEPH just selected jets:
assumption is BR$(H^+ \to \tau\nu) +$ BR$(H^+ \to q\bar{q}') = 1$.

$M_{H+} > 78.0$ GeV overall
83.4 GeV for BR$(H^+ \to \tau\nu) = 1$,
80.7 GeV for BR$(H^+ \to \tau\nu) = 0$

P. Colas [ALEPH], CERN-ALEPH-2001-016



## Flipped two Higgs doublet model: constraints

Top quark decay at the Tevatron:

For $\tan\beta \sim 1$, $H^+$ branching ratios about the same as in Type II model. Use Tevatron limits from DØ directly.

For $\tan\beta \gtrsim 3$, $H^+ \to c\bar{b} + c\bar{s} \simeq 1$. Translate CDF limits on BR($t \to H^+ b$) with BR($H^+ \to c\bar{s}$) = 1. $H^+ \to c\bar{b}$ should have only slightly worse $M_{jj}$ resolution.

| $M_{H^+}$ (GeV) | allowed $\tan\beta$ range |
|---|---|
| 100 | 1.40–28.8 |
| 120 | 1.10–26.2 |
| 150 | 0.53–65.8 |

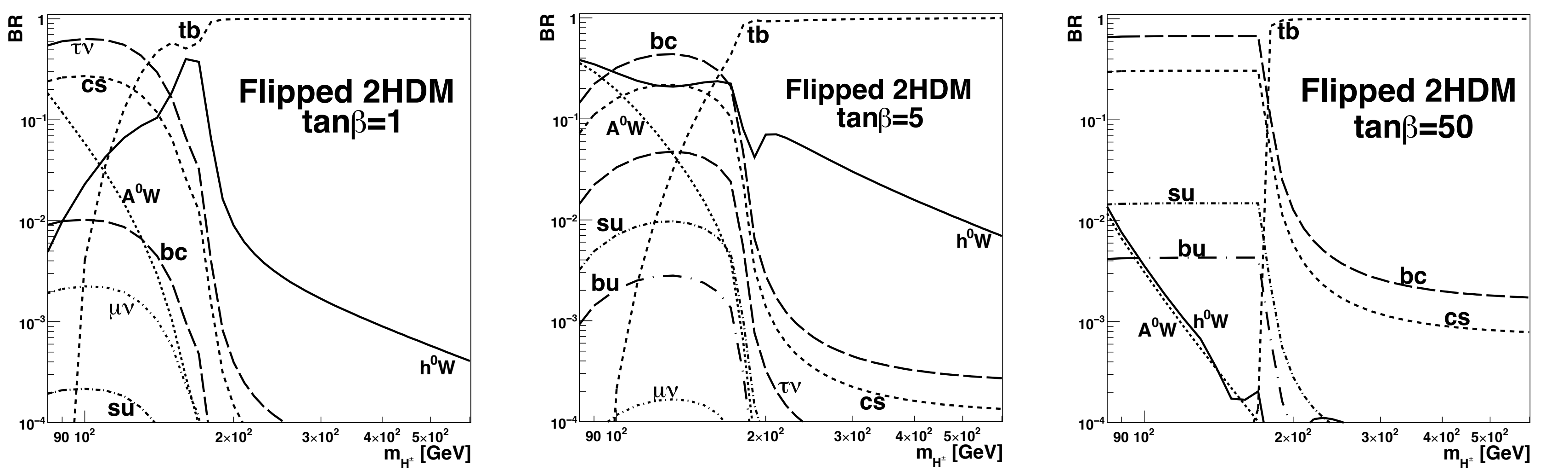
PRELIMINARY HEL & D. MacLennan, in preparation

## Flipped two Higgs doublet model: LHC prospects

Production couplings to quarks are identical to Type II 2HDM.

Below $tb$ threshold, decays are to $\tau\nu$ for $\tan\beta < 3$, $cb + cs$ for $\tan\beta > 3$.

Above $tb$ threshold, decays to $tb$ always dominate.




HEL & D. MacLennan, in preparation

## Flipped two Higgs doublet model: LHC prospects

Light charged Higgs: BR($t \to H^+ b$) same as Type II model, but $H^+ \to cb$, $cs$ at large $\tan\beta$! LHC studies with $H^+ \to \tau\nu$ not applicable.

Heavy charged Higgs: $H^+ \to tb$ decay dominates; $tH^+$ associated production cross section same as Type II model. Studies carry over verbatim.

$5\sigma$ discovery prospects (30 fb$^{-1}$): [based on ATLAS]

| $\tan\beta$ | $M_{H^+}$ range accessible (GeV) |
|---|---|
| 30 | 180–200 |
| 45 | 180–250 |
| 60 | 180–300 |

# Two-doublet model for neutrino masses

S.M. Davidson and H.E.L., arXiv:0906.3335

New field content:

- 3 right-handed two-component neutrinos $\nu_{R_i}$ (EW singlets)
- Second scalar doublet $\Phi_2$, same EW charges as SM Higgs

New symmetry: global U(1)

- $\nu_{R_i}$ and $\Phi_2$ have charge $+1$; all SM fields uncharged
- $M\nu_R\nu_R$ Majorana mass term forbidden by global U(1).

Lepton Yukawa couplings: structure fixed by U(1)

$$\mathcal{L}_{Yuk} = -y^{\ell}_{ij}\bar{e}_{R_i}\Phi_1^{\dagger}L_{L_j} - y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}_2^{\dagger}L_{L_j} + \text{h.c.}$$

To generate neutrino masses, break U(1) explicitly:

$$\begin{aligned} V &= m_{11}^2\Phi_1^{\dagger}\Phi_1 + m_{22}^2\Phi_2^{\dagger}\Phi_2 - [m_{12}^2\Phi_1^{\dagger}\Phi_2 + \text{h.c.}] + \frac{\lambda_1}{2}(\Phi_1^{\dagger}\Phi_1)^2 \\ &+ \frac{\lambda_2}{2}(\Phi_2^{\dagger}\Phi_2)^2 + \lambda_3(\Phi_1^{\dagger}\Phi_1)(\Phi_2^{\dagger}\Phi_2) + \lambda_4(\Phi_1^{\dagger}\Phi_2)(\Phi_2^{\dagger}\Phi_1) \end{aligned}$$

$\Phi_2$ gets a tiny vev $v_2 \sim$ eV.

## Particles and couplings

3 SM neutrinos are Dirac particles; no additional fermionic d.o.f.

4 new scalar degrees of freedom: $H^\pm$, $H^0$, $A^0$

Mixing effects: new scalars $\sim \Phi_2 + \mathcal{O}(v_2/v_1)\Phi_1$: completely negligible

Yukawa couplings of physical scalars:

$$\mathcal{L}_{Yuk} = \frac{m_{\nu_i}}{v_2} H^0 \bar{\nu}_i \nu_i - \frac{i m_{\nu_i}}{v_2} A^0 \bar{\nu}_i \gamma_5 \nu_i - \sqrt{2}\frac{m_{\nu_i}}{v_2}[U^*_{\ell i} H^+ \bar{\nu}_i P_L e_\ell + \text{h.c.}]$$

$U_{\ell i}$ is the Maki-Nakagawa-Sakata-Pontecorvo matrix

Constraint from big bang nucleosynthesis:

$$y_i^\nu \equiv \sqrt{2}\frac{m_{\nu_i}}{v_2} \lesssim \frac{1}{30}\left[\frac{M_{H^+}}{100 \text{ GeV}}\right]\left[\frac{1/\sqrt{2}}{|U_{\ell i}|}\right]$$

a little bigger than SM bottom quark Yukawa coupling

or $v_2 \gtrsim 2$ eV (scales with heaviest neutrino mass).

## Phenomenology: decays of new scalars

Fermionic modes: $H^+ \to \ell^+\nu$, $A^0/H^0 \to \nu\bar{\nu}$ (via $y_i^\nu$)

Bosonic modes: $A^0/H^0 \to W^+H^-$ or $H^+ \to W^+A^0/H^0$ (gauge int)

depends on masses: $M_A^2 = M_H^2 = M_{H^+}^2 + \lambda_4 v_1^2/2$

Most interesting decays: $H^+ \to \ell^+\nu$.

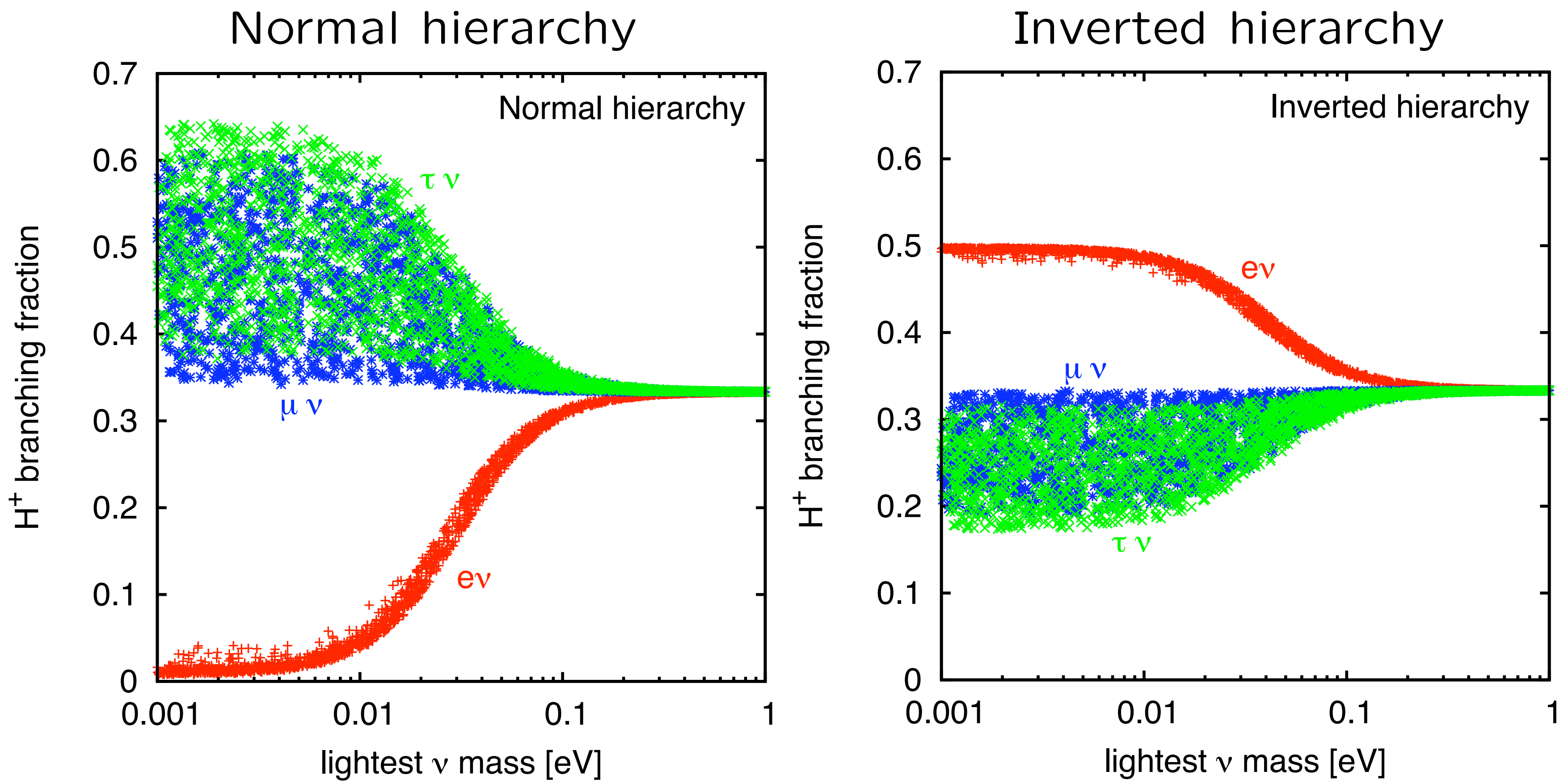
Assume $M_{A,H} > M_{H^+}$: no $H^+ \to W^+H^0/A^0$.

$$\Gamma\left(H^+ \to \ell^+\nu\right) = \frac{M_{H^+}}{8\pi v_2^2} \sum_i m_{\nu_i}^2 |U_{\ell i}|^2$$

Depends on expectation value of $m_\nu^2$ in *flavor* eigenstate $\nu_\ell$.

$$\mathrm{BR}(H^+ \to \ell^+\nu) = \frac{\sum_i m_{\nu_i}^2 |U_{\ell i}|^2}{\sum_\ell \left[\sum_i m_{\nu_i}^2 |U_{\ell i}|^2\right]}$$

Identical to $\Phi^+$ decay BRs in Type-2 seesaw model.




Behavior controlled by $\theta_{23} \sim 45^\circ$, $U_{e3}$ small.

Normal hierarchy: eigenstate 3 contains half of $\nu_\mu$, half of $\nu_\tau$, very little $\nu_e$

$\rightarrow$ BR($\mu\nu$) $\simeq$ BR($\tau\nu$) $\simeq 1/2$, BR($e\nu$) $\ll 1$

Inverted hierarchy: eigenstates 1 & 2 contain all of $\nu_e$, half of $\nu_\mu$, half of $\nu_\tau$

$\rightarrow$ BR($e\nu$) $\simeq 1/2$, BR($\mu\nu$) $\simeq$ BR($\tau\nu$) $\simeq 1/4$

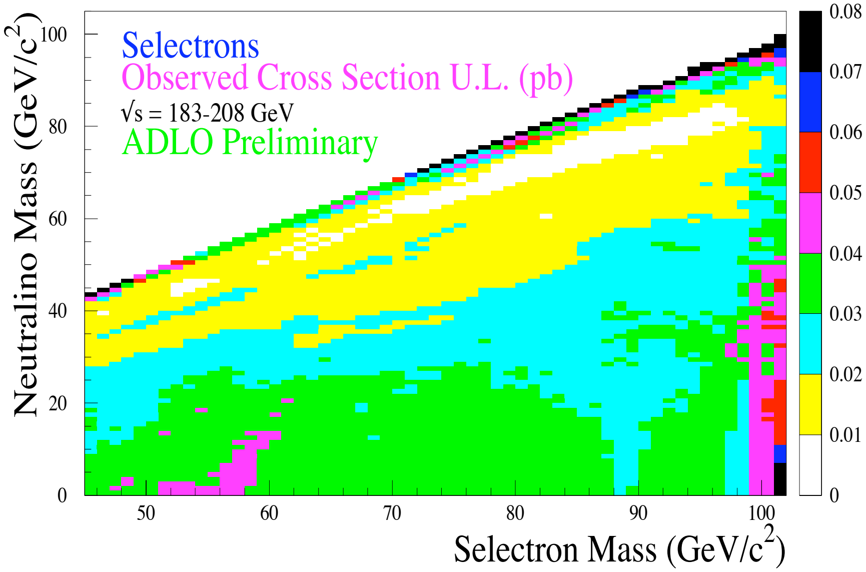
Degenerate spectrum

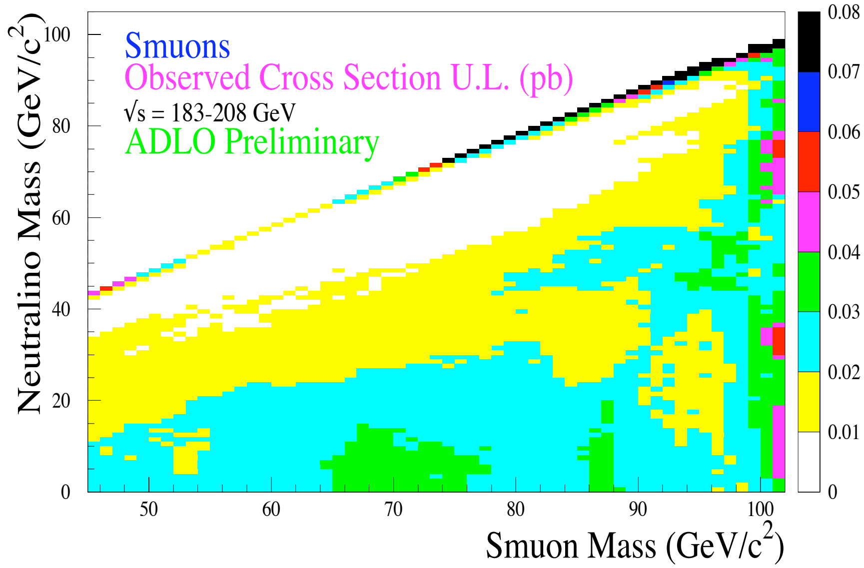
$\rightarrow$ all three BRs $= 1/3$.

## Constraints: LEP limit on $H^+H^-$

BR($H^+ \to \tau\nu$) too small for usual LEP charged Higgs search.

Look at LEP slepton searches instead with massless "neutralino".

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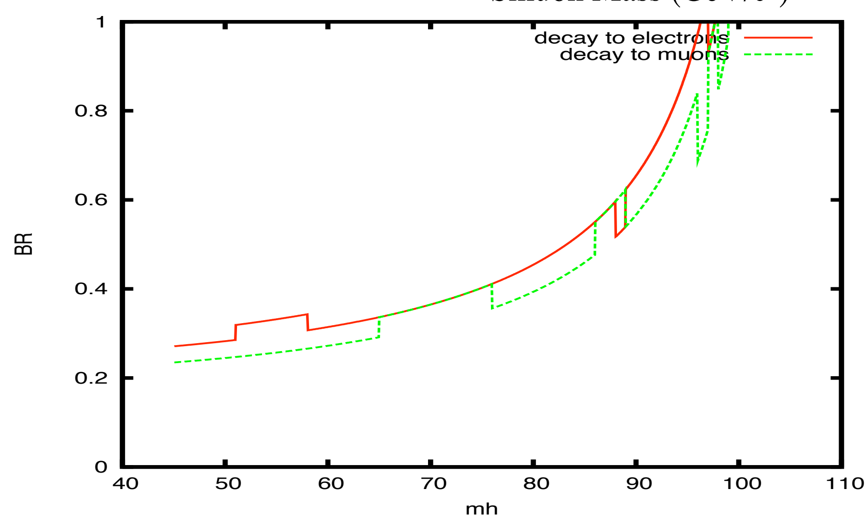
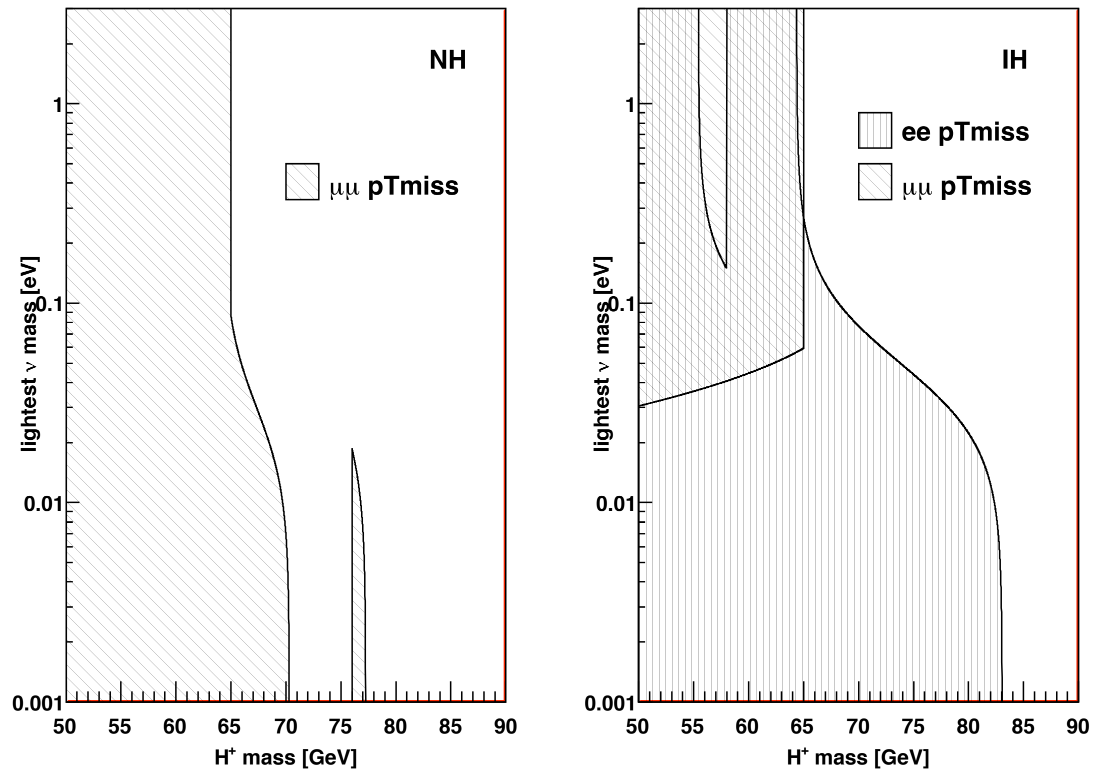



Put in $e^+e^- \to H^+H^-$ xsec, read off upper limit on BRs




NH: $\mu\mu p_T^{miss}$ channel strongest IH: $eep_T^{miss}$ channel strongest

# Phenomenology: LHC prospects

Rely on pair production: $pp \to H^+H^-,\ H^\pm A^0/H^0,\ A^0H^0$

- No coups to quarks; $H^+\ell_L^-\nu_R$ coupling $\lesssim 1/30$ (BBN constraint)
- Single production $\sim g^2 v_2$: super tiny

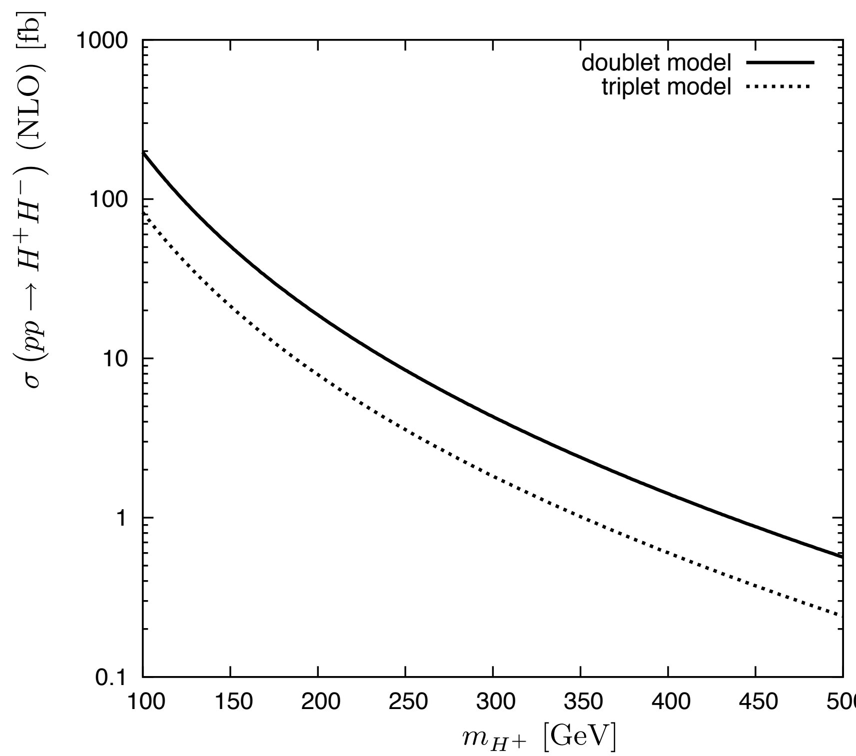
$H^+$ BR to $\mu\nu$ or $e\nu$ always $\geq 1/3$: $\ell^+\ell^- p_T^{miss}$ signature

Nice feature: $H^+H^-Z$ coupling.

This model: SU(2) doublet:
$g_{H^+H^-Z} = \frac{e}{s_W c_W}(\frac{1}{2} - s_W^2)$

Type-2 seesaw: SU(2) triplet:
$g_{\Phi^+\Phi^-Z} = \frac{e}{s_W c_W}(0 - s_W^2)$

Doublet cross section ∼2.5x larger than triplet.



## Phenomenology: LHC prospects

S.M. Davidson and H.E.L., work in progress

Signal: $pp \to H^+H^- \to \mu^+\mu^- p_T^{\rm miss}$, $e^+e^- p_T^{\rm miss}$, $e^\pm\mu^\mp p_T^{\rm miss}$

Major backgrounds: $W^+W^-$, $t\bar{t}$, $ZZ$, $Z\gamma$

Selection cuts:
Both leptons $p_T > 20$ GeV; $p_T^{\rm miss} > 30$ GeV
Veto jets with $p_T > 30$ GeV (kills most of $t\bar{t}$ background)
Veto $Z$ pole, 80 GeV $< M_{\ell^+\ell^-} <$ 100 GeV
$H_T' \equiv p_T^{\ell^+} + p_T^{\ell^-} + p_T^{\rm miss} > 200$ (600) GeV [for $M_{H^+} = 100$ (300) GeV]

Looks promising for discovery of $M_{H+} = 100$ GeV with 30 fb$^{-1}$ ($M_{H+} = 300$ GeV with 300 fb$^{-1}$) [preliminary]

## Conclusions

LHC studies for charged Higgs are well-developed... for the Type II model (and to some extent for Type I).

Other charged Higgs coupling patterns lead to different signal processes – both production and decay.

For some channels, LHC studies can be reinterpreted directly.
- Flipped 2HDM: $H^+ \to t\bar{b}$

For others, new phenomenological & experimental studies needed.
- Neutrino mass model: $H^+H^- \to \ell^+\ell^{(\prime)-}p_T^{\text{miss}}$ promising
- Lepton-specific 2HDM: can we do anything with $H^+H^- \to \tau\tau$?